Airborne Ku-band Polarimetric Radar Remote Sensing of Terrestrial Snow Cover

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Abstract—**Preliminary analyses of the POLSCAT data acquired from the CLPX-II in winter 2006-2007 are described in this paper. The data showed the response of the Ku-band radar echoes to snowpack changes for various types of background vegetation. We observed about 0.2 to 0.4 dB increases in backscatter for every 1 cm SWE accumulation for sage brush and agricultural fields. The co-polarized VV and HH radar resposnes are similar, while the corss-polarized (VH or HV) echoes showed greater resposne to the change of SWE. The data also showed the impact of surface hoar growth and freeze/thaw cycles, which created large snow grain sizes and ice lenses, respectively, and consequently increased the radar signals by a few dBs.**

Keywords—microwave remote sensing; snow water; radar

I. Introduction

Fresh water stored in snow on land is an important component of the global water cycle. In many regions of the world it is vital to health and commerce. High-resolution snow water equivalent (SWE) observation requirements were articulated by the Global Earth Observing System of Systems (GEOSS), Integrated Global Observing Strategy (IGOS), and WMO/WCRP Climate and Cryosphere (CliC) Project, Science and Co-ordination Plan. In 2005, the Cold Regions Hydrology High-resolution Observatory (CoReH$_2$0) proposal was submitted by the international cold land processes science community to the European Space Agency and was selected for proceeding to an 18-month study for space implementation. In addition, the Snow and Cold Land Processes (SCLP) mission was one of the satellite missions recommended for future NASA implementations in the recent earth science decadal study report [1]. Both missions include Ku-band radar.

In past studies ground-based microwave measurements at 5 to 35 GHz frequencies were obtained for snow with different wetness, depth, and SWE [2-9]. These historic measurements demonstrated the microwave radar response to snowpack for limited and/or artificial snow conditions. However, the impact of vegetation and terrain slope, nominally present in natural environment, has not yet been explored.

Recent analyses of spaceborne QuikSCAT scatterometer data, with footprint size on the order of 20 km, have suggested the presence of snowpack information in Ku-band radar observations for complex terrain [10, 11]. The match-up of the QuikSCAT data with the National Snow Analysis (NSA) on a nominal daily basis has been performed by the National Weather Service (NWS), National Operational Hydrologic Remote Sensing Center (NOHRSC) for the data acquired from July 2003 to April 2004 for several target sites, including the Mammoth pass in California, and three sites in Colorado. These target locations all have mountainous landscapes with a large percentage of forest cover. The QuikSCAT and NSA SWE scatter plots for all of the targeted areas indicate a monotonic increase of radar echo level for increasing SWE. In general for all of these areas, the change is about 1 dB radar echo level for 10 cm change of SWE. However, the effects of mixed terrain cover in coarse resolution QuikSCAT measurements have not allowed the evaluation of high-resolution hydrologic processes and development of retrieval algorithms for CoReH20 or SCLP missions, which require high resolution (100 m) radar observations.

Within the United States, the cold land processes research community has supported the second Cold Land Process Experiment (CLPX-II) during the 2006-2007 winter season in Colorado and winter 2007-2008 in Alaska [12]. The objective of the CLPX-II experiment is to acquire extensive Ku-band radar backscatter from various types of snow cover together with extensive in situ snow measurements. The experiment will serve as a testbed, providing the opportunity for the development of snow water retrieval algorithms and to test radiative transfer models for a variety of snowpacks.

II. POLSCAT/CLPX-II

In winter 2006-2007, we deployed the Ku-band polarimetric scatterometer (POLSCAT) built by the Jet Propulsion Laboratory (JPL) for three flight campaigns in Colorado. POLSCAT includes two-axis gimbals for a conically scanning, parabolic antenna at a constant elevation angle, which is controllable from 0 (nadir) to 65 degrees. For the CLPX-II campaigns, we installed POLSCAT on a Twin Otter aircraft, and operated the antenna at a 35 degree

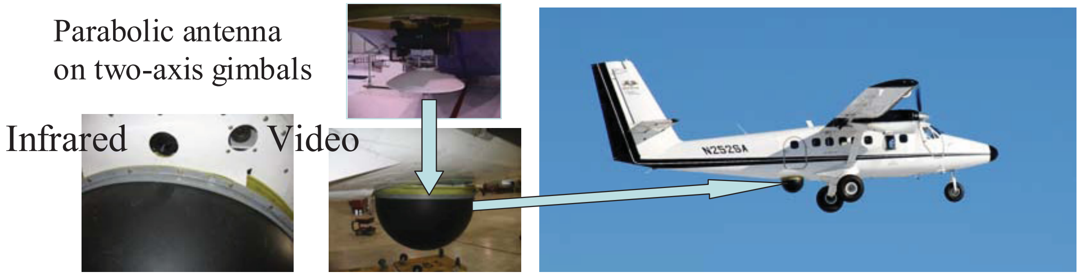

Figure 1. POLSCAT on the Twin Otter with two-asix gimbals for the conical scanning of the parabolic antenna at any incidence angle from 0 to 65 degrees. There are nadir-looking infrared and video cameras mounted adjacent to the POLSCAT antenna radome.

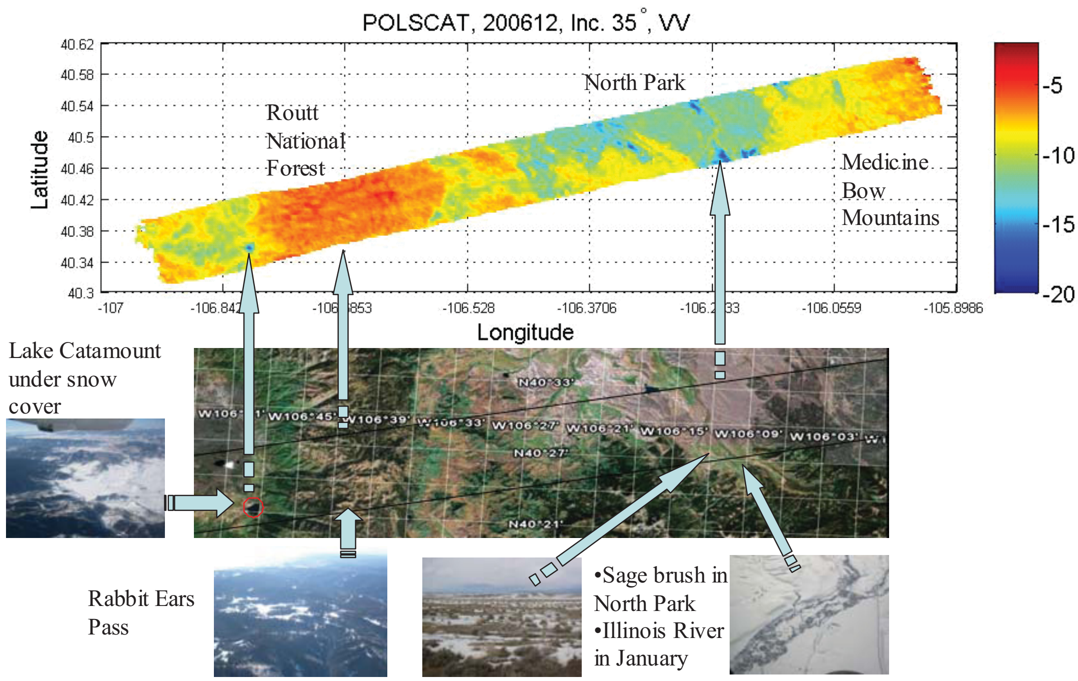

Figure 2. The test site is between two parallel black lines shown in the middle panel. The test site is about 90 km long from west to east and 9 km wide from south to north. The upper panel shows the color-coded POLSCAT VV radar data in dB, acquired in December 2006.

elevation angle (Fig. 1). A set of Twin Otter flights were also conducted at a 45 degree elevation angle to acquire data for cross-calibration with the QuikSCAT data. The key characteristics of POLSCAT are summarized in Table 1.

TABLE I. KEY POLSCAT CHARACTERISTICS

Frequency	13.9 GHz
Polarization	VV, HH, HV, and VH
Antenna Beamwidth	3 degrees
Incidence Angle	Commandable in flight from 0 to 65 deg
Azimuth Angle	Commandable from 0 to 360 degrees
Footprint resolution at 5000 ft above ground level	100 m (azimuth) and 120 m (range) at 35 degree incidence
Noise Equivalent Sigma0	<-40 dB
Calibration stability	<0.1 dB

Three intensive observing periods (IOP) with a total of 10 aircraft flights were completed in December 2006, January 2007, and February 2007. Each flight imaged an area of 9 km wide by 90 km long (Fig. 2). This area consisted of a variety of land use / land cover charachteristics, including coniferous and deciduous forests, sage brush, and agricultural fields. The site was chosen to enable the assessment of Ku-band radar response to snow accumulation for various types of terrain covers (Fig. 2). A nominal altitude of 14,000 ft above sea level resulted in an instrument height above ground level of approximately 4000-7000 ft over various locations in the study area. At this height the POLSCAT swath width for conical scanning at 35 degree elevation angle is about 1.7-3.4 km, depending on the ground elevation. We flew the POLSCAT on

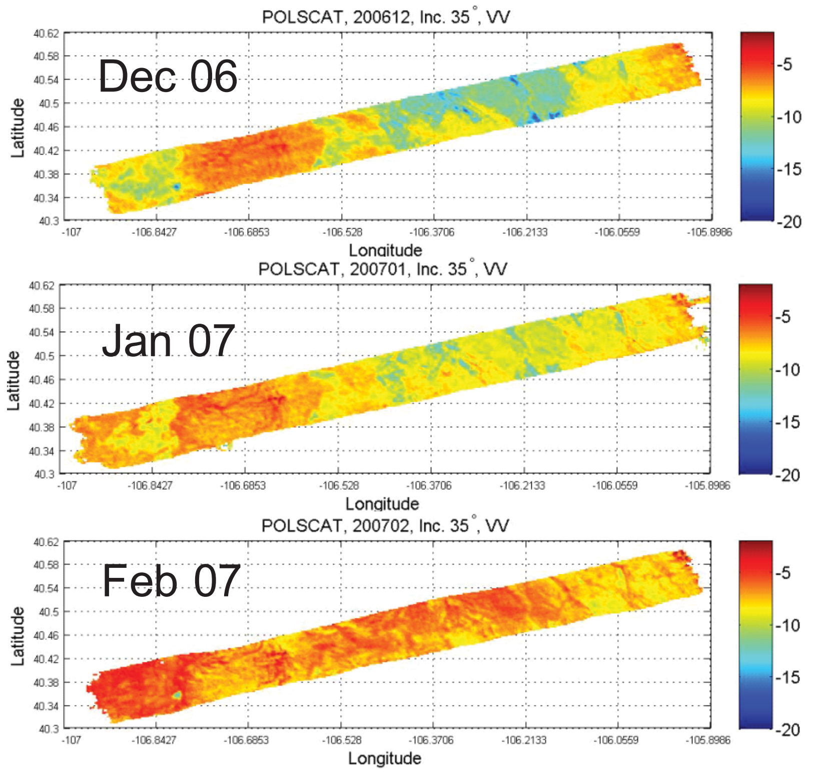

Figure 3. The POLSCAT VV radar images from top to bottom are for 2-5 Dec 2006 (IOP 1), 25-29 January 2007 (IOP 2), and 22-23 February 2007 (IOP 3). The VV data in dB are color-coded with the color key shown in the color bar.

the Twin Otter daily with six parallel flight tracks, equally spaced to achieve complete coverage of the entire 9 km by 90 km area.

III. Data Characteristics

The POLSCAT data were binned and averaged on 200 m grids for each IOP. The VV radar image for IOP 1 during 2-5 December 2006 (Fig 2, top) shows distinct backscatter levels for different terrain covers. The backscatter from the forests near the Rabbit Ears pass and in the eastern end of the test site showed strong radar backscatter of about -5 dB. The areas with sage brush cover or pasture near the Illinois River and the western end of the test site near Steamboat Springs had weaker backscatter of about -10 to -15 dB (green to light blue colors in Fig. 2). The weakest backscatter (deep blue) appeared to come from Lake Catamount and the river bed of the Illinois River.

Comparison of the VV data from three IOP campaigns (Figure 3) shows that the radar backscatter increased by about 2 dB over the sage brush areas in the North Park and the pasture fields near Steamboat Springs from IOP 1 to IOP 2 (25-29 January 2007). In contrast, the radar signals over forested areas near the Rabbit Ears pass showed a small reduction (~1 dB) from December to January. The signals for other radar polarizations, HH, VH and HV had similar features.

For direct indication of the radar response to snowpack, we plotted the radar signal changes in dB in Fig. 4. In December and January, the snowpack remained dry at all times. Our examination of the field data suggested that the SWE in North Park increased by about 5 cm from early December (IOP 1) to late January (IOP 2), corresponding to a radar backscatter change of about 2 dB. Consequently, the sensitivity of VV radar echoes was about 0.4 dB per 1 cm accumulation in SWE. Similar response was observed in the pasture fields to the west of Rabbit Ears pass.

During the field campaign, several "hourglass" (HG) test sites were selected with intensive spatial in-situ sampling. The size of each HG site was about 400 m by 400 m. The ground team dug snow pits at the center and corners to measure the snow density, SWE, depth and stratigraphy. The team also made four transects: two from the diagonal corners through the center and two on the edges of each site to sample the snow depth at about every 10-20 meters. The SWE for the HG sites were estimated as the product of the average snow density from the pit data and the average snow depth from transects. For each HG site, there were many radar footprints with their centers falling within the 400 m by 400 m box. For consistent comparison with the averaged SWE data, we included the radar data for averaging only if the center of the radat footprint was within 200 m from the center of the HG sites.

The average radar data are illustrated against the SWE data for the HG sites in Fig. 5. The HH and VV radar echoes increased by about 0.2 dB per cm SWE for the HG sites

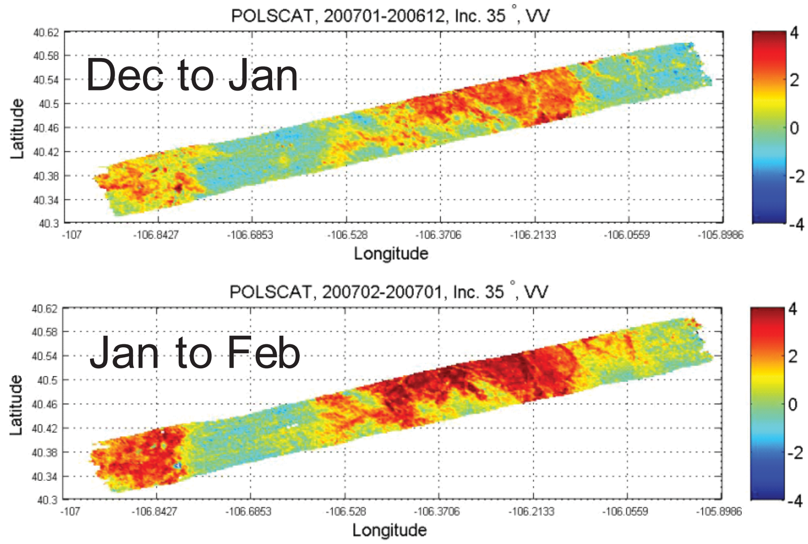

Figure 4. The changes of POLSCAT VV radar backscatter reflect the change of snow cover. The upper panel shows for the changes from early December 2006 to late January 2007, and the bottom panel shows the changes from January to February 2007.

located near Oak Creek and the HG sites inside the clear-cut areas near the Rabbit Ears pass. These seemed to be weaker than the response at the North Park sites. However, it can be noted that the North Park radar VV and HH responses were about 5 dB lower than those from the Oak Creek and Rabbit Ears HG sites in December 2006, when there was not much snow accumulation. The stronger radar scattering from the background vegetation in the Oak Creek and Rabbit Ears sites would make the contribution of the snow scattering relatively less in decibel.

In terms of polarized behaviour, the cross-polarized HV or VH scattering seems to be more sensitive to the snow accumulation than the co-polarized data VV or HH data. Fig. 5 showed that the cross-polarized signal changed by about 0.3 dB per cm SWE, about 50 percent stronger than VV and HH signal changes. This suggests that the relative contributions of volume scattering from snow and background (surface or vegetation) scattering differ between co- and cross-polarized radar returns.

The POLSCAT response (0.2 to 0.4 dB per 1 cm SWE) seemed to be significantly larger than that indicated by the QuikSCAT and NSA SWE matchup analysis [10, 11], which showed only about 0.1 dB increase for 1 cm SWE accumulation. Our hypothesis is that the QuikSCAT/NSA analysis was influenced by the mixture of forests, sage brush, and pasture in 20 km QuikSCAT footprints. The high resolution data from POLSCAT suggested that the forested areas underwent significantly less or slightly negative changes in radar backscatter from December to January. We analyzed the QuikSCAT data for 2006-2007 winter and carefully selected the QuikSCAT data centered in the sage brush area around the Illinois River in the North Park to minimize the effects of mixed pixels. The results showed that the QuikSCAT data did change by about 1-2 dB from December to January over the sage brush areas in the North Park, which became more consistent with the POLSCAT observations.

From IOP 2 to IOP 3 (22-23 February 2007) the sage brush and pasture fields had more dramatic VV increases of about 3-5 dB (lower panel in Fig. 4). Comparing the middle and bottom panels in Fig. 3 shows that the radar backscatter of the snow-covered sage brush and pastures became stronger than that of the forested areas. Preliminary examination of in-situ observations indicated that there was wide spread depth hoar in the snowpack in late February. Ice lenses were also present, which were caused by several melting and refreezing events starting in early February. The large snow grains in the depth hoar and the ice lenses were apparently the cause of the significant 3-5 dB increase.

IV. Summary

The high resolution POLSCAT data acquired from the CLPX-II in winter 2006-2007 showed the response of the Ku-band radar echoes to snowpack changes for various types of background vegetation. We observed a Ku-band radar response of about 0.2 to 0.4 dB increases for every change of 1 cm SWE for snow-covered sage brush and pasture. The data showed the potential impact of the presence of depth hoar and the impact of freeze/thaw cycles, which resulted in ice lens growth and consequently increased the radar backscatter by a few dBs. The data further suggested that the cross-polarized radar response was more sensitive to the presence of depth hoar and ice lenses.

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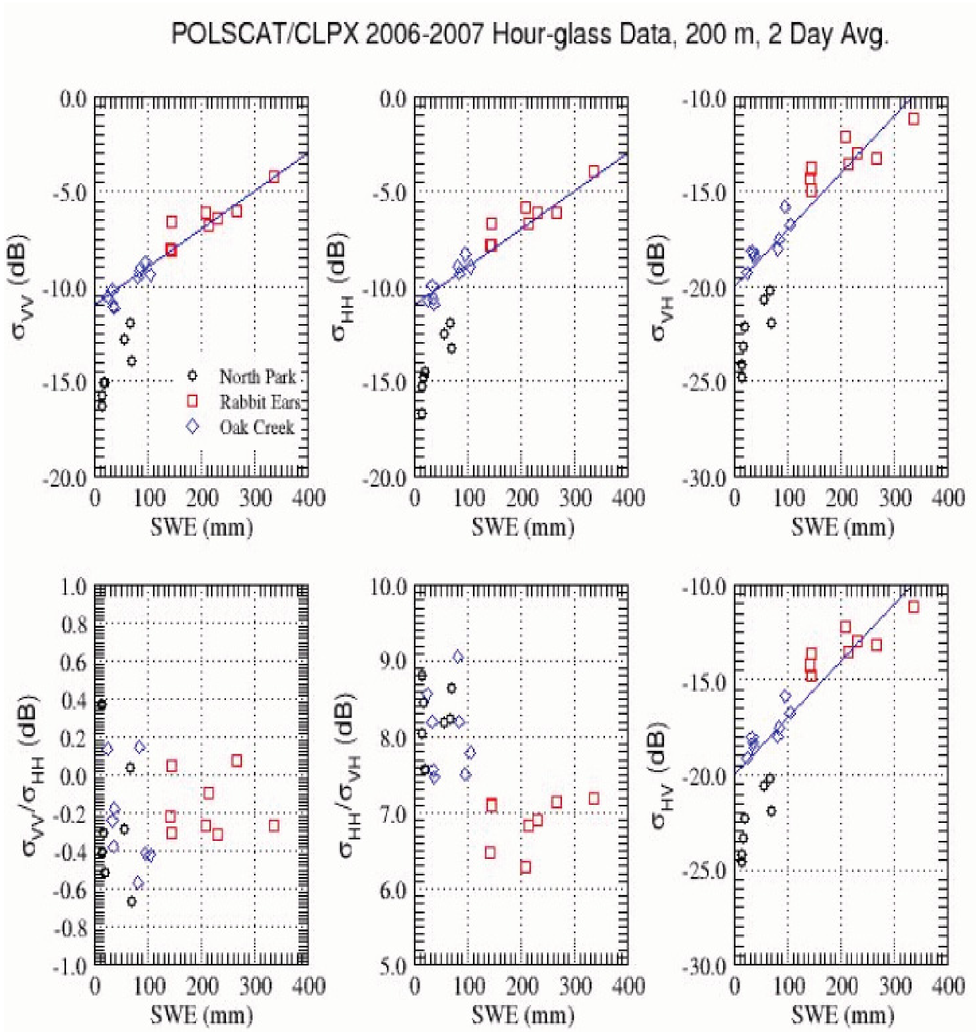

Figure 5. Comparison of POLSCAT radar data with the snow samples from the hourglass (HG) test sites. The snow depth at several selected test sites were sampled spatially in hourglass spatial patterns. These test sites are denoted as "hourglass" sites. Each HG site is aout 400 m by 400 m. In additional to the snow depth measurements, snow pits were dug at the center and corners of the test site to sample snow density, grain size and stratigraphy. The snow depth measurements were averaged and multiplied with the snow density observations from the pits to represent the SWE contained in each hourglass site. The POLSCAT data acquired within 200 m from the center of the HG site were also averaged for comparison with the SWE estimate.

and Space Administration. Also, the work described here included the contributions by the National Operational Hydrologic Remote Sensing Center and the US Forest Service.

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